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THIRD INTERNATIONAL CONFERENCE ON RAPIDLY QUENCHED METALS

JEFF PERKINS.

19 September 1978

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The technical content of the Third International Conference on Rapidly Quenched Metals, held 3-7 July 1978 at the University of Sussex, is reviewed. Papers on Techniques of rapid quenching, metallic glass formation, crystallization from the amorphous state, applications of metallic glasses, and other subjects covered at the conference are described.

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THIRD INTERNATIONAL CONFERENCE ON RAPIDLY QUENCHED METALS

The Third International Conference on Rapidly Quenched Metals, held 3-7 July 1978 at the University of Sussex, Brighton, England, was sponsored and organized jointly by the Materials Science Group of the University of Sussex and the Metals Society (Program Committee Chairman Professor R.W. Cahn of the University). The program included more than 125 papers, which came, remarkably, from 18 different countries, and attracted about 235 registrants. The venue and organization were outstanding, and the Conference must be considered a great success. In fact, the location was certainly part of the attraction, or reward, of attending this meeting, set in the tranquil green hills that envelop the University of Sussex campus, where the facilities are transformed, as is typical for British universities in summer, into an efficient conference center. This eminently favorable atmosphere was established less than five miles from the center of Brighton, with its memorable beachfront promenade and Royal Pavilion, and the nearby chalk cliffs of east Sussex. One afternoon of the Conference was given over to a selection of optional field trips, one of which involved a seven-mile hike over the undulating Seven Sisters cliffs. One of the energetic participants in this ordeal, wherein one follows a path along the cliff top that cycles between about 100 ft and 500 ft above the sea, was inspired to remark that if one were to venture too near the cliff's edge, one's own self might end up going "splat" on the rocks below. This remark relates to the original method of producing samples of metastable alloys from the melt, namely by propelling a charge of liquid metal against a cooled plate.

For readers who are not actively involved in this specialty area of research (and there seemed to be many such "interested observers" at this Conference) it might be useful to define the topic area in more detail. The term "rapidly quenched (RQ) metals", lately adopted by those in the field, is intended to include the more specific term "metallic glasses" (amorphous metals). One might well ask: "A rose by any other name is still a rose, but what is a metallic glass?" This is the nagging question which probably inspired adoption of the more general, relatively noncommittal phrase "rapidly quenched metals" for this class of materials. For the uninitiated, a metallic glass, as one has a chance of guessing from the seemingly inconsistent term, is a material that, although normally metallic, is rendered structurally into an amorphous state, usually by very rapid quenching from the liquid. However, since the resulting material may not be totally glassy (amorphous), or perhaps not at all, or may not remain glassy, particularly as time and temperature increase, the designation RQ is the safer, inclusive term. When RQ metals are not in fact amorphous, they are generally

microcrystalline in form, i.e., have unusually fine microstructural features that are also of interest. To confuse things even more, an amorphous state can be produced by other means than rapid quenching of the liquid, such as by vapor quenching, ion beam bombardment, or laser glazing, the latter two methods affecting only a certain surface region. These related phenomena were also discussed at the Conference.

Metallic glass alloy compositions typically are composed of either one or more transition metals (Fe, Ni, etc.) or a noble metal (Pd, Au, Cu, etc.) and one or more metalloid elements (P, B, Si, etc.). The "classical" (most-studied-to-date) alloys of these types are based around compositions such as Fe_4B and Pd_4Si. At this Conference, by way of example, the two most-discussed alloys were of the compositions $Fe_{80}B_{20}$ and $Fe_{40}Ni_{40}P_{14}B_6$. These are related to the commercial "METGLAS" family of metallic glass alloys marketed by the Allied Chemical Company. Currently, the common form of metallic glass product is thin strip (typically less than 100μm in thickness), with one of the current practical problems being to produce larger-area, thicker, and higher-quality sheet material.

Metallic glasses are of special interest for many reasons. From the practical viewpoint, amorphous metals are variously found to have high strength, corrosion resistance, resistance to radiation damage, zero or negative coefficient of resistivity, low ultrasonic attenuation, magnetic softness (low coercivity and magnetostriction), and other unusual properties. The study of RQ materials has attracted the interest of scientists in many basic disciplines, including metallurgists, solid state physicists, chemists, crystallographers, surface scientists, experts in heat transfer and fluid dynamics, and engineers and technologists in various specialities. Research on these materials provides insight into a number of basic problems such as phase stability, crystallization kinetics, diffusion, structural defects, etc. In fact, work to date may be regarded as having strongly emphasized the basic physical questions, with much less attention to engineering and technological application. The wide-ranging interest in these materials was reflected at Sussex by the large number of countries active in research and the range of scientific disciplines involved. The combination of personalities and expertise which this produced was quite unusual at a special topic conference, and seemed to create a more lively intellectual atmosphere than perhaps is typical.

Reviewing the history behind this Third Conference, the Second Conference was held at MIT in November 1975, with 97

papers (Second International Conference on Rapidly Quenched Metals; proceedings published by MIT Press in 1976 and in a special issue of Journal of Materials Science); the First Conference was held in Bresla, Yugoslavia in 1970, with 46 papers (First Conference on Metastable Metallic Alloys; proceedings published in Fizika, Vol. 2 Suppl. 2). Proceedings of the Sussex meeting are optimistically expected to be published by the end of the year, although the multilingual (all papers written in "English") editing task will be formidable. The Fourth Conference, "RQ81" has been scheduled for 1981 in Japan.

The Conference program was divided into seven topic areas: Techniques of Rapid Quenching, Metastable Crystalline Alloys, Formation and Stability of Metallic Glasses, Physical Properties of Rapidly Quenched Alloys, Magnetic Properties of Glasses, Application of Rapidly Quenched Metals, Structure and Flow of Metallic Glasses (and a few papers on Corrosion of Metallic Glasses). These are essentially the same areas assigned at the 1975 conference, with the addition of a session on applications. In some cases, the program contained some redundancy, which may be useful in the early stages of research; for example the subjects of stability and crystallization kinetics were heavily subscribed. On the other hand, only slight coverage was given to other areas, such as methods of producing useful metallic glass material (there was very little on vapor quenching, for example), basic questions of alloy phase stability, and prediction of glass-forming tendency. The Conference was in single-session form, with each topic area introduced by a 30-minute key paper, followed by a number of 15-minute contributed papers. Also, 58 of the total 128 papers were presented as posters, in groups of about a dozen per day, placed in the lobby just outside the meeting hall; this worked quite well in terms of access and time available.

The lead paper of the techniques session was presented by H.A. Davies (Univ. of Sheffield, UK), who reviewed some of the technologically promising schemes for producing metallic glasses, such as melt-spinning (jetting onto a rotating piece), melt extraction, melt extrusion, twin-rolling of a jet, etc. He also gave attention to theoretical aspects of metallic glass formation and tried to identify the important factors that affect glass-forming tendency in metallic systems, such as the alloy melting temperature (T_m), glass transition temperature (T_g), crystallization temperature (T_c), and properties of the melt such as viscosity. Davies suggested that a simple index, T_g/T_m, could be used to predict glass forming ability, with

higher values indicating easier glass formation (glassy state obtainable for slower cooling rates). The glass-forming ability and the glass-phase stability have important technological implications, in determining the maximum glassy section thickness that can be produced, and the maximum service temperature, respectively. It would be of great value to be able to predict these behaviors accurately for new alloys, and, although the T_g/T_m index may be an oversimplification from a fundamental viewpoint, it seems to have definite usefulness. There were few attempts at this Conference to generalize and formulate principles from the diverse data, yet efforts in this direction seem to have special merit, especially to observers outside the mainstream who are trying to sort out the essence of the field. Later in the program, B.C. Giessen (Northeastern Univ., Boston, MA) and co-workers contributed a paper that also attempted to delineate criteria for glass formation. This paper was couched more in terms of classical alloy phase theory, and the significance of such parameters as atomic size ratio, e/a ratio, and melting point depression were discussed. In my opinion this effort to consolidate ideas regarding glass formation and stability was one of the most innovative contributions to the meeting, an especially refreshing experience after the long series of talks, each dealing with a particular narrow range of data. In any case, Giessen demonstrated perhaps more facility for prediction of glassy behavior than otherwise observed during this Conference.

Other papers in the session on techniques dealt with the fundamental nature of the actual phenomenon of rapid liquid quenching. For example, such features as splat puddle geometry, which relates to important operational factors such as spin velocity in the melt spin and melt extraction techniques, and the effect of inert gas and vacuum environments were considered. These studies included excellent photographic and cinematographic evidence, by H. Hillmann and H.R. Hilzinger (Vacuumschmelze GmbH, Hanau, West Germany) and J.L. Walter and H.H. Liebermann (General Electric Research Lab., Schenectady, NY), respectively. S.D. Dahlgren (Battelle Pacific Northwest Labs., Richland, WA) reviewed vapor quenching techniques, a technologically promising area that appeared to be undersubscribed at this Conference. An unusual aspect of this method for developing amorphous materials is that thick deposits can be built up. Dahlgren also reported on differences between amorphous material (Fe_4B) produced by liquid-quenched and vapor-deposited methods; one significant observation being that the crystallization temperature of vapor-deposited material is about 50°C higher

than for liquid-quenched material.

An exciting paper contributed by R. Clampitt *et al* (UKAEA, Culham Laboratory, Abington, Oxon), dealt with electric field atomization from the melt, which is a possible method for producing glassy metal surface coatings and a possible alternative to conventional vacuum deposition techniques. In this scheme, an electric field of appropriate sign is applied to the melt surface to create the well-known Taylor cone phenomenon; these fine-peaked features on the surface break into high-velocity streams of ionized particles that may then impinge on and coat a target surface; the droplets are typically micron-size but can be as small as single atomic ions, so that the technique in the limit approaches ion implantation.

The use of standard ion implantation techniques was also discussed to some extent. This technique is appropriate only when it is desirable to render a specific surface layer into an amorphous or metastable state. In this scheme, one of the usual attractions of ion implantation, namely the ability to produce metastable (surface) alloy compositions that are otherwise unobtainable, is augmented by the possibility of forming a glassy layer with its special properties. The concept of formation of a glassy layer can be modeled in terms of the rapid quenching of displacement spikes that momentarily approximate internal liquid regions, or alternatively as simply the accumulation of damage that eventually obtains the amorphous state.

An additional variation on methods to obtain RQ metals, the use of lasers and electron beams for "surface glazing," was described in a paper by P.R. Strutt (Univ. of Connecticut, USA) and co-workers in the case of tool steels, and by S.M. Copley (Univ. of So. California, USA) and co-workers in the case of superalloys. Here the situation is distinct from conventional RQ ribbon material, as there is a pronounced structural gradient from the surface inward. The microstructural aspects of this received some attention, but the full meaning in terms of properties seems yet to be defined.

R.W.K. Honeycombe (Cambridge Univ., UK) presented the invited paper on RQ crystalline alloys relating to situations where the glassy state is not obtained. These materials are of great interest and represent perhaps an even larger range of immediate applications than metallic glasses, since conventional alloys of all types that may have very poor glass-forming ability can nevertheless be rendered into various metastable and/or microcrystalline conditions by rapid melt-quenching. Thus

steels, aluminum alloys, titanium alloys, and super-alloys may be created with special microstructural features such as fine grains (sub-micron level), extended solid solubility (and attendant strengthening) metastable phases, and fine dendritic structures. Also, there may well be modification of subsequent phase transformations. For example, fine grains, as is well known, tend to retard martensitic transformation, lowering Ms. In micro-grained rapidly quenched alloys, this effect tends to be quite resistant to annealing, as reported by B. Canter and co-workers (Univ. of Sussex, UK).

To date, studies on metastable crystalline alloys have been essentially limited to the response of rapidly quenched conventional alloys. There has been little work on alloys specially designed for this kind of processing, which may offer additional improvements in properties. Cooling rates used to obtain materials in this class may be as low as 10^2 to 10^3 degrees per second, far less dramatic than for glassy alloys, where 10^6 is usually essential to obtain the glassy state. In addition to Honeycombe's review paper on the principles of rapidly quenched crystalline alloys, N.J. Grant (MIT, USA) presented a review paper on applications. This paper was a singular departure from other presentations at the Conference in that it emphasized the practical state-of-the-art of RQ crystalline materials. A similar "plain talk" presentation would have been useful for glassy alloys. There is considerable interest in the properties of consolidated rapidly quenched powders of superalloys and high-speed tool steels produced by some form of gas atomization. Generally speaking, these materials have higher strength, lower ductility, lower high-temperature creep resistance, and better hot workability than conventional cast superalloys. Consolidated materials made from powders tend to exhibit considerable scatter in mechanical properties owing to gas pores and oxide inclusions. Alloy compositions can be varied beyond the usual range in order to impart improvements not obtainable via conventional solidification, such as better low-cycle fatigue behavior or enhanced oxidation resistance.

Currently, one of the key problems is to reduce the complexity and cost of both the RQ powder production and consolidation procedures, and a few contributed papers touched on this. B.H. Kear (United Technologies Research Center, E. Hartford, CO) described a new process by which powders are produced through a combination of centrifugal atomization of the melt, with high mass flow helium gas quenching of the atomized spray. One of the justifications for the work is to eliminate the

typical blocky MC-type carbides from the superalloy micro-structures through rapid cooling, while subsequently precipitating δ' and fine MC particles. While on the subject of RQ conventional alloys, it is interesting to note that typical metallic glass compositions (Fe_4B, etc.) are usually quite poor in properties in the crystalline state, as compared with conventional alloys. This can largely be attributed to the unusually high concentration (typically 10% or more) of nonmetallic elements. When such alloys obtain their equilibrium condition, the microstructure is usually undesirable from the standpoint of mechanical properties.

It was obvious from the number of contributions that crystallization of metallic glasses is a topic of major interest and importance. This problem was ably reviewed by M.G. Scott (Univ. of Sussex, UK), who pointed out that there are both scientific and technological reason for the study of metallic glass crystallization. Scientifically, the phenomenon offers an opportunity to study crystal growth in highly undercooled media, whereas from a practical standpoint, the stability of the glassy state is often essential. Additionally, crystallization from the glassy state, by purposely annealing, may offer routes to new and otherwise unobtainable microstructures. This opens up a whole new arena of consideration for alloy designers and has considerable interest for those concerned with phase stability and phase transformation kinetics among other subjects. Invariably, the phases which first form on crystallization are not the equilibrium alloy phases. Also, there are a variety of reaction types that may occur, depending on the alloy system and annealing temperature, and so the form of the crystallized microstructure can be quite diverse. It was in the area of crystallization that the Conference program exhibited the most redundancy, with papers from at least half a dozen different countries on the crystallization of $Fe_{80}B_{20}$-type alloys alone.

On the third and fourth days, the Conference swung away from topics familiar to physical metallurgists to discussions more oriented toward physics of metals, as various physical, electrical, and magnetic properties were considered. The subject of super-conductivity received particular attention. This area was reviewed by W. Johnson (California Institute of Technology, Pasadena, CA) and papers by J. Bevk (Harvard Univ., Cambridge, MA) and others concerned themselves with the behavior of amorphous superconducting alloys of compositions such as $Nb_3(Al, Si)$ and $Nb_3(Al, Ge)$. Johnson pointed out that an important feature of amorphous superconductors is that the electron mean free path is very small, on the order of atom distances; the electron mfp is related to the coherence length and so the penetration

depth; coherence length is on the order of 500-1000 Å for a crystalline material, but only about 10 Å for an amorphous material; thus the inversely related penetration depth is much larger for the amorphous state, as is the upper critical field, Hc_2, while the lower critical field, Hc_1, is smaller. Bevk described the opportunity one has to manipulate the microstructure of a superconducting alloy through techniques of rapid quenching/annealing; this is desirable because it offers an opportunity to optimize the "hardness" of a superconducting material by the dispersion of flux-pinning microstructural features, analogous to the dispersion of dislocation-inhibiting features in mechanical strengthening. Such features as grain boundaries, precipitates, and voids are possible flux-pinning agents, with spacings on the order of 100-200 Å desirable. In cases where grain boundaries are the primary pinning feature available, rapid quenching provides a special route to grain size on the scale required. Another unusual aspect of RQ superconducting alloys, as reviewed in an unaccompanied (naturally) poster from the Soviet Union, is that the composition of the stoichiometric A15 compound, e.g., Nb_3Si, can be modified considerably while obtaining a much higher critical temperature.

Magnetic properties of amorphous alloys were reviewed by C.D. Graham, Jr. (Univ. of Penn., Philadelphia, PA). Currently one of the prime applications of metallic glasses is in this realm, i.e., the use of Fe_4B-type alloys as magnetic shielding material, and Allied Chemical Company currently produces a commercial product which consists of a basketweave of glassy alloy strips (each strip about 2-mm wide). Graham's excellent coverage of the magnetic properties area pointed out that glassy alloys sometimes approach the "ideal" soft magnetic material: they can be strongly magnetic, with thick domain walls and low anisotropy energy; they are homogeneous, have high electrical resistivity and low eddy current damping; and they are low in magnetostriction. Possible applications, in addition to magnetic shielding, include tape recorder heads and Permalloy-type applications in power transformer devices. Problems in developing these applications include processing difficulties, low saturation magnetization values, and instability of the glassy state.

Structural descriptions of metallic glasses and modeling of their deformation behavior were reviewed by F. Spaepen (Harvard Univ., Cambridge, MA), and nearly the entire final day was devoted to contributions involving experimental determinations of mechanical properties for a variety of alloy compositions. Regarding the fundamental subjects of structure and flow of metallic glasses, Spaepen reviewed structural models based

on random packing of spheres, which are topologically distinct from any crystal structure and imply description in terms of an "ideal" amorphous structure. Atomic transport in these structures can then be described in terms of "defects" in this ideal structure. In contrast to crystal defects, which tend to be localized and well defined on an atomic scale, amorphous structural defects are more diffuse in nature, and are best described as fluctuations in the ideal structure. Plastic flow in such structures can be divided into two main types: Homogeneous flow (at high temperatures or low stresses) and inhomogeneous flow (at low temperatures and high stresses). The structural defects that govern homogeneous flow above the glass transition temperature are determined by the system's equilibrium structure. Below the glass transition temperature, they are determined by its thermal history (quenching, annealing, etc.) During inhomogeneous flow the defect structure is determined by a dynamic equilibrium of stress-induced creation and diffusion-controlled annihilation of defects. This leads to localization of the flow in shear bands and, finally, fracture by a mechanism similar to the Taylor instability.

The general subject of applications of RQ alloys, although a fascinating topic, was not particularly well covered in any single paper, which may have been because the organizers desired to have a basic science emphasis in the Conference. Collectively, however, contributions at the Conference reflected a wide range of applications, many of which have been mentioned already. Unfortunately, the session nominally intended to cover applications did not review the subject in an organized way, and although the published proceedings may do better, it may be worthwhile to summarize briefly some of the range of applications that seem plausible for RQ metals. Applications for glassy metals may be classified on the basis of special physical, mechanical, and chemical properties. Additionally, rapidly quenched crystalline alloys have their own set of attractions. Thus we can review some potential applications on the basis of these various categories, briefly citing the nature of the key properties in comparison to normal (crystalline) material. It should be cautioned that generalizations regarding properties are tenuous, particularly when sweeping across the broad range of metallic glass alloys.

On the basis of their electrical and magnetic properties, amorphous Fe_4B-type alloys are generally strongly magnetic, have high electrical resistivity, low eddy current damping, the possibility of very low or zero magnetostriction, high permeability, and low energy losses; however, they tend to

have relatively low values of saturation magnetization. Many of these attributes are quite composition- and processing-dependent. It should be noted that the amorphous state is also structurally very homogeneous, and that many properties can be controlled in a given alloy through annealing. Two notable applications that could take advantage of the unusual magnetic properties include magnetic shielding and power transformer cores.

As mentioned earlier amorphous superconducting compositions tend to have short coherence length and thus larger penetration depths, with higher Hc_2 and Tc, and lower Hc_1. Also, because the amorphous state cannot be further disordered, such materials are resistant to radiation damage and so may be useful in nuclear (including fusion) reactor applications.

On the basis of their mechanical properties, amorphous metals tend to be strong and not very ductile. Direct load-bearing applications for metallic glasses were for the most part not considered at the Conference. In fact, only a few papers presented mechanical properties data, mostly in the form of microhardness measurements. More sophisticated measurements and analyses of the mechanical flow behavior of glassy metals were presented by the group headed by A.S. Argon (MIT, Cambridge, MA), and by Masumoto and co-workers (Tohoku Univ., Japan). In a more applied contribution, the use of short (1 mm) melt-extraction-produced "fibers" for reinforcement in concrete and castable refractures was described by R.E. Maringer and C.E. Mobley (Battelle Columbus Labs, OH). One of the advantages of the resulting composite material is greater thermal shock resistance; these fibers may or may not be completely amorphous, depending on their size, the alloy, etc.

Chemically and electrochemically, the major feature that distinguishes amorphous metals from normal alloys is their composition and microstructural homogeneity. There are no grain boundaries, precipitates, etc., to be preferentially attacked, which suggests that certain corrosion modes (e.g., intergranular corrosion) would not be operative. It would be of great interest to develop further electrochemical data on such materials, to delineate their relative activities, polarization behavior, etc. Several contributions were made by workers from Tohoku University and Northeastern University regarding the corrosion properties of metallic glasses. Although some interesting data were presented, as yet there are no established principles regarding the electrochemical behavior of amorphous alloys, and since their behavior is quite different from corresponding crystalline material, this is

an area that should become quite interesting as it receives more attention.

In spite of the fact that this was the Third International Conference on RQ Metals this is still a very young field; in fact, as reflected in the Conference titles, even the name of the field is in a state of fluctuation. As would be expected for an emerging area of science and technology, RQ metals is in the process of defining itself, particularly in terms of the primary directions that research will take. Although the scientific content of the subject is definable in fairly familiar terms of metal physics, the field seems to be in a state of ebb and flow, i.e., it does not have a consistent momentum in any single direction. In this sense, it is a very exciting field at present, and promises to yield considerable valuable insight as times goes on. As the participants at Sussex wended their way through a varied and pleasant experience, one came to realize that what may at first seem to be a specialized niche of metallurgy is a treasure trove of insight for many scientific disciplines. We would seem to be guaranteed numerous scientific and technological revelations as a result of continuing research in this area.

Formal Opening of the Conference by Sir Denys Wilkinson (Vice-Chancellor of the University of Sussex)

SESSION ONE—TECHNIQUES OF RAPID QUENCHING

Chairmen: P. Duwez (California Institute of Technology, Pasadena, USA) and H. Jones (University of Sheffield)

Rapid quenching techniques and formation of metallic glasses
H. A. Davies (University of Sheffield)

Discussion

On the formation of amorphous ribbons by the melt spin technique
H. Hillmann and H. R. Hilzinger (Vacuumschmelze GmbH, Hanau, West Germany)

A study of the formation of amorphous ribbon using high-speed motion pictures
J. L. Walter (General Electric Corporate Research and Development, Schenectady, New York, USA)

Low temperature quenching techniques
Z. Maronhić, B. Leontić and E. Babić (University of Zagreb, Yugoslavia)

Advances in melt extraction
R. E. Maringer and C. E. Mobley (Battelle's Columbus Laboratories, Ohio USA)

Discussion

Light Refreshments and Poster Session (see opposite)

Electric field atomisation from the melt
R. Clampitt, K. L. Aitken and L. Gowland (UKAEA, Culham Laboratory) and M. G. Scott (University of Sussex)

Solidification of eutectic alloys over a heat pipe
S. N. Ojha, K. Chattopadhyay and P. Ramachandrarao (Banaras Hindu University, Varanasi, India)

Production of amorphous alloys by ion implantation
A. Ali and P. J. Grundy (University of Salford) and L. T. Chadderton, W. A. Grant and E. Johnson (H. C. Orsted Institute, Copenhagen, Denmark)

Discussion

Lunch

SESSION TWO—METASTABLE CRYSTALLINE ALLOYS

Chairmen: H. Warlimont (Vacuumschmelze, Hanau, West Germany) and H. Matyja (Warsaw Polytechnic, Poland)

Rapidly quenched crystalline alloys
R. W. K. Honeycombe (University of Cambridge)

Discussion

Splat-quenched tungsten steels
J. J. Rayment and B. Cantor (University of Sussex)

Melt-extraction of high alloy steels and superalloys
J. V. Wood and J. Bingham (University of Cambridge)

Surface segregation in rapidly solidified superalloys
B. H. Kear and P. N. Ross (United Technologies Research Center, East Hartford, Connecticut, USA)

Martensite in splat-quenched Fe and Fe-Ni
F. Duflos and B. Cantor (University of Sussex) and Y. Inokuti (Kawasaki Steel Corporation, Chiba City, Japan)

Discussion

Light Refreshments and Poster Session (see opposite)

Mechanism of solidification at rapid rate; implications for development of new techniques
M. C. Flemings (Massachusetts Institute of Technology, Cambridge, USA)

Rapid quenching of aluminium alloys
T. N. Anantharaman, P. Ramachandrarao, C. Suryanarayana, S. Lele, K. Chattopadhyay and G. V. S. Sastry (Banaras Hindu University, Varanasi, India) and H. A. Davies (University of Sheffield)

Extended solid solubility, grain refinement and age-hardening in Al-1 to 13wt%Zr rapidly quenched from the melt
E. Sahin and H. Jones (University of Sheffield)

Discussion

End of Session

Posters

(17) *On the cooling conditions and solidification structures of gas atomised metals*
B. Frykendahl (Royal Institute of Technology, Stockholm, Sweden)

(18) *Epitaxial growth of alloy films by laser melt quenching*
S. M. Copley, M. Bass, E. W. Van Stryland, D. Beck and O. Esquivel (University of Southern California, Los Angeles, USA)

(19) *Examination of some rapid quenched cobalt-tungsten carbide alloys*
D. Duževič and A. Bonefačić (University of Zagreb, Yugoslavia)

(20) *Metastable phases in rapidly quenched Fe-B alloys*
H. Franke, U. Herold, U. Köster and M. Rosenberg (Ruhr University, Bochum, West Germany)

(21) *Structure of Al-3 to 18wt%Ni gun-quenched from the melt*
R. Hales, J. H. Vincent and H. Jones (University of Sheffield)

(22) *Structure and properties of some splat-quenched alloys with copper*
E. M. Savitsky, Yu. W. Efimov, G. G. Muchin and T. M. Frolova (Baikov Institute for Metallurgy, Moscow, USSR)

(23) *Structural analyses of laser surface melted tool steels*
P. R. Strutt and H. Nowotny (University of Connecticut) and B. H. Kear (United Technologies Research Center, East Hartford, Connecticut, USA)

(24) *X-ray diffraction study of splat-quenched Ag-Sn alloys*
A. M. Tonejc and A. Kirin (University of Zagreb, Yugoslavia)

(25) *Rapid solidification of a memory alloy*
J. V. Wood, A. Crosley and W. M. Stobbs (University of Cambridge)

(26) *Investigation of point defects in ultra-rapidly quenched Al samples by lattice parameter measurements*
E. Girt, A. Kuršimovic, T. Mihać-Kosanović and N. Njuhović (Physics of Metals Laboratory, Sarajevo, Yugoslavia)

(27) *Exafs study on Al-Cu alloys*
A. Fontaine, P. Lagarde, C. Noguera, D. Raoux and D. Spanjaard (Université Paris-Sud) and A. Naudon (Laboratoire de Metallurgie Physique, Poitiers, France)

(28) *Solution and precipitate hardening in melt quenched micropoly-crystalline Ti-Al-V-base multi-component alloys*
E. W. Collings, H. L. Gegel, R. E. Maringer and C. E. Mobley (Battelle's Columbus Laboratories, Ohio, USA)

(29) *Splat quenching of high-speed tool steels*
J. Niewiarowski and H. Matyja (Warsaw Polytechnic, Poland)

SESSION THREE—FORMATION AND STABILITY OF METALLIC GLASSES

Chairmen: N. J. Grant (Massachusetts Institute of Technology, Cambridge, USA) and J. F. Sadoc (Université Paris-Sud, France)

Stability and crystallisation of metallic glasses
M. G. Scott (University of Sussex)

Discussion

Temper embrittlement of amorphous alloys
R. S. Williams and T. Egami (University of Pennsylvania, Philadelphia, USA)

The effect of oxygen additions on the properties of amorphous transition metal alloys
D. E. Polk, C. Dubé and B. C. Giessen (Northeastern University, Boston, Massachusetts, USA)

Critical cooling rate for glass formation of Pd-Cu-Si alloys
M. Naka and T. Masumoto (Tohoku University, Sendai) and Y. Nishi (Tokai University, Hiratsuka, Japan)

Glass transition, stability and crystallisation of TeGe glasses
M. Lasocka, H. Matyja, B. Dabrowski and J. Kochanski (Warsaw Technical University, Poland)

Discussion

Light Refreshments and Poster Session (see opposite)

Formation and thermal properties of novel metallic glasses
R. O. Elliott (Los Alamos Scientific Laboratory, New Mexico) and B. C. Giessen, M. Fischer, D. E. Polk, R. St. Amand, J. Hong and L. Kabacoff (Northeastern University, Boston, Massachusetts, USA)

Metastable crystalline phases and glasses in ternary Fe-C alloys
E. Hornbogen and I. Schmidt (Ruhr University, Bochum, West Germany)

Mechanical properties and thermal stability of new type amorphous high-carbon alloy steels
A. Inoue, T. Masumoto, S. Arakawa and T. Iwadachi (Tohoku University, Sendai, Japan)

Discussion

Lunch

SESSION FOUR—FORMATION AND STABILITY OF METALLIC GLASSES (continued)

Chairmen: L. E. Tanner (Allied Chemical Corporation, Morristown, New Jersey, USA) and P. H. Shingu (Kyoto University, Japan)

The formation and stabilities of some iron and nickel based glassy alloys
I. W. Donald and H. A. Davies (University of Sheffield)

Crystallisation of amorphous semiconductors and metals
U. Herold, U. Köster, G. Hillenbrand and S. Hock (Ruhr University, Bochum, West Germany)

On the stability and crystallisation of amorphous $Fe_{1-x}B_x$ alloys
T. Kemény, I. Vincze and B. Fogarassy (Central Research Institute for Physics, Budapest, Hungary) and S. Arajs (Clarkson College of Technology, Potsdam, New York, USA)

The stability and transformations of $Fe_{80}B_{20}$ metallic glass
A. L. Greer and J. A. Leake (University of Cambridge)

Crystallisation of some amorphous alloys
J. L. Walter and S. F. Bartram (General Electric Company, Schenectady, New York, USA)

Crystallisation of amorphous Fe-P-C alloys
P. H. Shingu, K. Shimomura, R. Ozaki, K. Osamura and Y. Murakami (Kyoto University, Japan)

Discussion

Light Refreshments and Poster Session (see opposite)

The crystallisation of $(Fe_{100-x}Ni_x)_{83}B_{17}$ amorphous alloys
B. G. Lewis (Inco (Europe) Ltd, Birmingham) and H. A. Davies (University of Sheffield)

Crystallisation characterization of amorphous $Ni_{60}Nb_{40}$
C. Clay and N. J. Grant (Massachusetts Institute of Technology, Cambridge, USA)

Formation and stability of metallic glasses containing Zr
P. G. Zieliński, B. Dabrowski, A. Bonicki, K. Budziak, A. Całka, H. Matyja, A. Janicki, M. Kijek and J. Ostatek (Warsaw Polytechnic, Poland)

A contribution to the interpretation of the structure of Pd-Si amorphous alloys
P. Duhaj, P. Mrafko and P. Butvin (Slovak Academy of Sciences, Bratislava, Czechoslovakia)

Discussion

End of Session

Posters

(48) *Resistometric analysis of the phase transformations in amorphous $Fe_{40}Ni_{40}B_{20}$ alloys*
E. Babić, Z. Marohnić, D. Pavuna and B. Leontić (University of Zagreb, Yugoslavia)

(49) *Stability and mechanical properties of metglass 2826A*
J. W. Drijver, A. L. Mulder, W. C. Emmens and S. Radelaar (State University Utrecht, The Netherlands)

(50) *Correlation between the temperature coefficient of the electrical resistivity and the crystallisation temperature of amorphous Fe-Ni-B alloys*
H. Hillmann and H. R. Hilzinger (Vacuumschmelze, Hanau, West Germany)

(51) *Thermo-sonometric investigation of the crystallisation of metallic glasses*
O. Hunderi and K. Lonvik (Norwegian Institute of Technology, Trondheim)

(52) *Thermal stability of ductility in amorphous metallic alloys*
M. Nagumo, T. Takahashi, T. Arai and T. Hasegawa (Nippon Steel Corporation, Kawasaki, Japan)

(53) *Annealing effects in metal-metal amorphous alloys*
N. A. Pratten and M. G. Scott (University of Sussex)

(54) *Glass transition interval in metallic glasses*
P. Ramachandrarao (Banaras Hindu University, Varanasi, India)

(55) *Mössbauer effect study of structural relaxation and of early stages of crystallisation in $Fe_{80}B_{20}$ glass*
Z. Wronski, J. Suwalski and H. Matyja (Warsaw Polytechnic, Poland)

(56) *Rapid quenching in ferrimagnetic oxides*
C. Chaumont, H. Laville, J. B. Monteil and J. C. Bernier (CNRS, Strasbourg, France)

(57) *On the crystal chemistry of stable and metastable intermetallic phases with readily glass forming compositions*
B. C. Giessen and D. E. Polk (Northeastern University, Boston, Massachusetts) and J. C. Barrick (Wilmington College, Ohio, USA)

(58) *Amorphous semi-conducting oxides*
J. Livage and A. Revcolevschi (University of Paris, France)

(59) *Oxygen stabilization in Mg-Zn amorphous alloys prepared by sputtering*
R. Messier and R. Roy (The Pennsylvania State University, Philadelphia, USA)

(60) *On the stability of metallic glasses*
H. Beck (University of Basle, Switzerland)

(61) *Physical properties of Ti-Be-Si glass ribbons*
L. E. Tanner (Allied Chemical Corporation, Morristown, New Jersey, USA)

SESSION FIVE—PHYSICAL PROPERTIES OF RAPIDLY QUENCHED ALLOYS

Chairmen: F. E. Luborsky (General Electric Company, Schenectady, New York, USA) and B. Leontić (University of Zagreb, Yugoslavia)

Metastable superconducting materials
W. Johnson (California Institute of Technology, Pasadena, USA)

Discussion

Superconducting properties of liquid-quenched $Nb_3(Al, Si)$ and Nb_3 (Al, Ge)
J. Bevk (Harvard University, Massachusetts, USA)

Sputtering of high T_c superconducting metastable A15 compounds
R. E. Somekh and J. E. Evetts (University of Cambridge)

Thermally-activated internal friction peaks in amorphous films of Nb_3Ge and Nb_3Si
B. S. Berry and W. C. Pritchett (IBM Research Center, Yorktown Heights, New York, USA)

Preparation and physical properties of metallic glasses
M. Liard, R. Oberle, M. Müller, K. P. Ackermann, H. Rudin, H. U. Künzi and H.-J. Güntherodt (University of Basle, Switzerland)

Discussion

Light Refreshments and Poster Session (see opposite)

Vapor quenching techniques
S. D. Dahlgren (Battelle Pacific Northwest Laboratories, Richland, Washington, USA)

Mossbauer effect and electrical resistivity in splat-quenched La-Au alloys
S. Nanao, J. Sugiura, Y. Ohji and H. Ino (University of Tokyo, Japan)

Influence of heat treatments on the optical properties of amorphous CoP and NiP
J. Rivory and B. Bouchet (Université P. and M. Curie, Paris, France)

Discussion

Lunch

Posters

(70) *Amorphous metals: unique test material for electron transport theory*
P. J. Cote and L. V. Meisel (Watervliet Arsenal, New York, USA)

(71) *Low temperature specific heat of the amorphous metal alloys $(Fe_{100-x}Cr_x)_{79}P_{13}B_8$ for x = 2,4*
T. C. Long, T. A. Donnelly and D. G. Onn (University of Delaware, Newark, USA) and J. Durand (Université Louis Pasteur, Strasbourg, France)

(72) *Electrical resistivity of amorphous Fe_xSn_{1-x} alloys*
G. Marchal, Ph. Mangin, M. Piecuch, B. Rodmacq and Chr. Janot (Université de Nancy, France)

(73) *Low temperature specific heat measurements on amorphous alloy ribbons*
T. B. Massalski and K. T. Hartwig (Carnegie-Mellon University, Pittsburgh, Pennsylvania, USA), U. Mizutani (Nagoya University, Japan) and R. W. Hopper (University of California, Livermore, USA)

(74) *Superconductivity in pseudobinary alloys of A15 phases after fast quenching from liquid state*
P. Müller and V. Matthes (Zentralinstitut für Festkörperphysik und Werkstoffforschung der AdW, Dresden, East Germany) and E. M. Savitsky and Y. Y. Jefimov (A. A. Baikov Institute of Metallurgy of the Academy of Sciences of the USSR, Moscow)

(75) *A refractory glass alloy of Fe_7W_6*
R. Wang, M. D. Merz, J. L. Brimhall and S. D. Dahlgren (Battelle Northwest Laboratories, Richland, Washington, USA)

SESSION SIX—MAGNETIC PROPERTIES OF GLASSES

Chairmen: F. Gardner (Office of Naval Research, Boston, Massachusetts, USA) and T. Masumoto (Tohoku University, Sendai, Japan)

Magnetic properties of amorphous alloys
C. D. Graham, Jr. (University College, Cardiff and University of Pennsylvania, Philadelphia, USA)

Discussion

Magnetoelastic effects of some ferromagnetic glasses
G. Hausch (Swiss Aluminium Ltd, Neuhausen) and E. Török (Institut Straumann, Waldenburg, Switzerland)

Magnetic and transport properties of amorphous ferromagnetic $(Fe_{100-x}M_x)_{79}P_{13}B_8$ alloys obtained by splat-cooling ($M = Mn, Cr, V, 1 \leq x \leq 4$)
J. Durand (Laboratoire de Structure Electronique des Solides, Strasbourg, France) and C. Thompson (California Institute of Technology, Pasadena, USA)

Anomalous thermal expansion, ΔE effect, and invar and elinvar characteristics of some Fe-based amorphous alloys
K. Fukamichi, H. Hiroyoshi and T. Masumoto (Tohoku University, Sendai) and M. Kikuchi (The Research Institute of Electric and Magnetic Alloys, Sendai, Japan)

The micromagnetic properties of an amorphous alloy
J. E. Evetts, W. Howarth and M. R. J. Gibbs (University of Cambridge)

Discussion

Light Refreshments and Poster Session (see opposite)

Magnetic interactions in amorphous rare earth base alloys
K. J. Buschow (Philab, Eindhoven, The Netherlands)

Theoretical studies of amorphous metallic alloys containing rare-earth elements
R. Ferrer, R. Harris, S. H. Sung and M. J. Zuckermann (McGill University, Montreal, Canada)

Discussion

Lunch

SESSION SEVEN—APPLICATIONS OF RAPIDLY QUENCHED METALS

Chairmen: R. W. K. Honeycombe (University of Cambridge) and C. D. Graham (University of Pennsylvania, Philadelphia, USA)

Applications of metastable crystalline alloys
N. J. Grant (Massachusetts Institute of Technology, Cambridge, USA)

Discussion

Development of amorphous alloys with high magnetic induction
S. Hatta, T. Egami and C. D. Graham, Jr. (University of Pennsylvania)

The magnetic properties of Fe-B amorphous alloys
F. E. Luborsky, H. H. Liebermann and J. J. Becker (General Electric Corporate Research and Development, Schenectady, New York, USA)

Amorphous magnetic alloys (Fe, Co, Ni)-(Si,B) with high permeability and its thermal stability
S. Ohnuma (The Research Institute of Electric and Magnetic Alloys, Sendai) and T. Masumoto (Tohoku University, Sendai, Japan)

Amorphous metal alloys for improved magnetic shielding
J. P. Dismukes and G. J. Sellers (Allied Chemical Corporation, Florham Park, New Jersey, USA)

Discussion

Light Refreshments and Poster Session (see opposite)

Rapid cooling processing techniques applied to blends of polyethylene and paraffin wax
Z. Bashir and M. R. Mackley (University of Sussex)

Explosive fabrication of rapidly quenched metal alloys
C. Cline, J. Mahler, M. Finger and W. Kuhl (University of California, Livermore, USA)

Potential uses of rapidly solidified alloys in gas turbine engines
A. R. Cox (Pratt and Whitney Aircraft, Florida) and E. C. van Reuth (US Defense Advanced Projects Agency, Virginia, USA)

Discussion

End of Session

Posters

(91) *Soft magnetic properties of Fe-rich amorphous alloys*
H. Fujimori, T. Masumoto, S. Ohta, T. Kato, H. Morita and K. Nakamoto (Tohoku University, Sendai, Japan)

(92) *Hall resistivity of Fe and Fe-Ni based amorphous alloys*
R. Malmhäll and G. Bäckström (University of Umeå, Sweden, K. V. Rao (Clarkson College of Technology, Potsdam, New York, USA) and S. M. Bhagat (University of Maryland, USA)

(93) *Galvanomagnetic effects in $Fe_xNi_{80-x}P_{14}B_6$ metallic glasses*
Z. Marohnic, E. Babic, J. Ivkov and A. Hamzic (University of Zagreb, Yugoslavia)

(94) *Spin wave resonance in amorphous ferrimagnetic GdCoMoAr alloy film*
T. Mizoguchi and R. Kobliska (IBM Watson Research Center, Yorktown Heights, New York, USA), S. Maekawa (Tohoku University Sendai) and T. Imazu (Gakushuin University, Tokyo, Japan)

(95) *Superparamagnetic behaviour of $(Fe_{0.04}Ni_{0.96})_{80}P_{10}B_{10}$ metallic glass*
J. Schneider and A. Handstein (Adw der DDR, Dresden) and K. Zaveta and F. Zounova (Institute of Solid State Physics, Prague, Czechoslovakia)

(96) *Measurement of the low field paramagnetic susceptibility of an amorphous alloy, e.g. $Au_{75}Si_{19}Fe_6$*
G. Zibold (University of Konstanz, West Germany)

(97) *Magnetic iron-silicon-boron metallic glasses*
K. Hoselitz (University of Sussex)

(98) *Replacement of boron by carbon in Fe-B-C amorphous alloys*
F. E. Luborsky, J. J. Becker and H. H. Liebermann (General Electric Corporate Research and Development, Schenectady, New York, USA)

SESSION EIGHT—STRUCTURE AND FLOW OF METALLIC GLASSES

Chairmen: G. S. Cargill III (IBM, Yorktown Heights, New York, USA) and B. Cantor (University of Sussex)

Structure and flow of amorphous alloys
F. Spaepen (Harvard University, Cambridge, Massachusetts, USA)

Discussion

The structure of, and plastic flow in a Bragg bubble glass
A. S. Argon and H.-Y. Kuo (Massachusetts Institute of Technology, Cambridge, USA)

Models for amorphous palladium-silicon and similar glasses, with defined local coordination
P. H. Gaskell (University of Cambridge)

Surface features, mechanical properties, and their interrelationships in melt-spun multicomponent Fe-P-C-base metallic glass ribbon fibers
E. W. Collings, C. E. Mobley, H. L. Gegel and R. E. Maringer (Battelle Memorial Institute, Columbus, Ohio, USA)

Hot forming of a metallic glass
J. Patterson, A. L. Greer, J. A. Leake and D. R. H. Jones (University of Cambridge)

Discussion

Light Refreshments and Poster Session (see opposite)

Techniques for determining very short room temperature lifetimes of amorphism developed by rapid quenching
R. B. Pond, Sr. and C. R. Sirian (The John Hopkins University, Baltimore, Maryland, USA)

Radiation stability of metal alloy glasses
C. Cline, R. Hopper and C. Rowe (University of California, Livermore, USA)

A study of diffusion and crystallisation of vacuum-deposited and liquid-quenched amorphous alloys by high voltage electron microscopy
M. Kiritani, T. Yoshiie and F. E. Fujita (Osaka University, Japan)

Discussion

Lunch

SESSION NINE—STRUCTURE AND FLOW OF METALLIC GLASSES (cont): CORROSION OF METALLIC GLASSES

Chairmen: D. Turnbull (Harvard University, Cambridge, Massachusetts, USA) and J. V. Wood (University of Cambridge)

Structure of amorphous alloys studied by energy dispersive x-ray diffraction method
T. Egami (University of Pennsylvania, Philadelphia, USA) and Y. Waseda (University of Toronto, Canada)

Compositional study on short-range structure of Pd-Si and Fe-B amorphous alloys
T. Fukunaga, M. Misawa, K. Fukamichi, T. Masumoto and K. Suzuki (Tohoku University, Sendai, Japan)

Investigation of the structure of amorphous $Fe_{80}B_{20}$
H. G. Wagner, U. Gonser and H. Schertz (Universität des Saarlandes, Saarbrücken, West Germany)

Atomic scale structure of amorphous sputtered Nb_3Ge
G. S. Cargill and C. C. Tsuei (IBM, Yorktown Heights, New York, USA)

Local structure and dynamic disorder of Fe and Ni in metallic glasses by EXAFS spectroscopy
J. Wong, J. L. Walter and F. E. Luborsky (General Electric Corporate Research and Development, Schenectady, New York) and F. W. Lytle (The Boeing Company, Seattle, Washington, USA)

A survey of the current experimental structural information on metallic glasses
Y. Waseda (University of Toronto, Canada)

Discussion

Light Refreshments and Poster Session (see opposite)

Corrosion behaviour of amorphous metals
T. Masumoto, K. Hashimoto and M. Naka (Tohoku University, Sendai, Japan)

Corrosion behaviours of amorphous cobalt-base alloys
M. Naka, K. Hashimoto and T. Masumoto (Tohoku University)

Corrosion resistance of ion-plated metallic films
W. B. Nowak and M. F. Collins (Northeastern University, Boston, Massachusetts, USA)

Discussion

Closing Remarks

Posters

(116) *Microstructural variability and magnetic anisotropy in amorphous Gd-Co-based sputtered films*
G. S. Cargill III (IBM, Yorktown Heights, New York, USA)

(117) *The viscosity-temperature relation of metallic glasses*
E. Coleman and C. E. Miller (Bell Laboratories, Murray Hill, New Jersey, USA)

(118) *Structure, stability and mechanical properties of liquid-quenched Fe-based and Ni-based amorphous alloys*
M. Doi, H. Kosaki and T. Imura (Nagoya University, Japan)

(119) *Correlation between microhardness and magnetic properties in amorphous Fe-Ni alloys*
T. Ivezić, M. Očko, E. Babić, M. Stubičar and Z. Maronhić (University of Zagreb, Yugoslavia)

(120) *Structure of amorphous $Cu_{57}Zr_{43}$ alloy determined by TOF pulsed neutron diffraction*
T. Kudo and T. Mizoguchi (Gakushuin University, Tokyo) and N. Watanabe, N. Niimura, M. Misawa and K. Suzuki (Tohoku University, Sendai, Japan)

(121) *Deformation localization, plastic instabilities and fracture in a $Pd_{80}Si_{20}$ glass*
J. Megusar, A. S. Argon and N. J. Grant (Massachusetts Institute of Technology, Cambridge, USA)

(122) *Slip deformation and critical shear stress of amorphous Pd-Si alloy*
T. Murata (J. G. C. Corporation, Yokohama) and T. Masumoto and M. Sakai (Tokoku University, Sendai, Japan)

(123) *Diffusion of hydrogen in amorphous alloys-effect on mechanical properties*
B. Rondot, E. Navarro, M. Cornet and M. da Cuhna Belo (CNRS, Vitry-sur-Seine, France)

(124) *Cu Zr amorphous structure – an example for small atoms – large atoms amorphous metallic alloy*
J. F. Sadoc (Université de Paris-Sud, France)

(125) *A comparison of atomic and electronic structures between electro-deposited and melt-quenched Ni-P amorphous alloys* K. Suzuki, F. Itoh, T. Fukunaga and T. Honda (Tohoku University, Sendai, Japan)

(126) *The structure of amorphous metal-metal alloys*
Y. Waseda (University of Toronto, Canada) and H. S. Chen (Bell Laboratories, Murray Hill, New Jersey, USA)

(127) *Structural studies of amorphous electroless deposited CoP*
I. C. Baianu (University of Cambridge)